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EXPERIMENTAL INVESTIGATION OF
VENTILATED CAVITIES

by

Richard James Kinnear

Thesis Supervisor:
Professor Patrick Leehey

May 17, 1968

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EXPERIMENTAL INVESTIGATION OF VENTILATED CAVITIES

by

RICHARD JAMES KINNEAR

LIEUTENANT, UNITED STATES NAVY

B.S., United States Naval Academy

(1963)

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Naval Engineer and the Degree of

Master of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1968

ABSTRACT

Experimental Investigation of Ventilated Cavities

Richard James Kinnear

Submitted to the Department of Naval Architecture and Marine Engineering on 17 May 1968 in partial fulfillment of the requirements for the Master of Science degree in Mechanical Engineering and the Professional Degree, Naval Engineer.

A wedge with a 3.5 inch chord and a half-angle of 4.1 degrees is tested in the MIT Propeller Tunnel. No pulsations were observed on the cavity. Thus, the attempt to verify the theory that pulsations are possible in an infinite medium (without a free surface) is inconclusive.

Although there exist a variance in the cavitation number between theory and experiment, the data plotted show that the general shape of the curve for a 4.1 degree wedge is correct. The primary discrepancy is in the pressure recording methods.

Visual observations become difficult when ventilated cavities are generated in the test section. It takes only about 5 to 10 seconds for the air introduced into the cavity to recirculate through the tunnel.

Thesis Supervisor: Patrick Leehey
Title: Professor of Naval Architecture

TABLE OF CONTENTS

	Page
Abstract.	ii
Acknowledgements.	iv
List of Figures.	v
Symbols.	vi
I. INTRODUCTION.	1
II. PROCEDURE.	3
III. RESULTS.	10
IV. DISCUSSION OF RESULTS.	27
V. CONCLUSIONS AND RECOMMENDATIONS.	30
VI. REFERENCES.	31

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LIST OF FIGURES

	Page
Figure I. Front view of test section	4
Figure II. Rear view of test section	4
Figure III. RPM versus Flow velocity	8
Figure IV. Cavity Resonance Conditions	11
Figure V. Cavitation number versus Chord length to cavity length ratio	17
Figure VI. Drawing of the general nature of the re-entrant jet of a natural cavity.	22
Figure VII. Drawing of the general nature of the re-entrant jet of a ventilated cavity.	23
Figure VIII. Ventilated cavity with free surface.	25
Figure IX. Bottom view of Figure VIII.	25
Figure X. Comparison between cavitation number based on vapor pressure and cavitation number based on measured cavity pressure.	29
Figure IVa. Equivalent Mach number versus steady part of cavitation number.	13
Table I. Theoretical results for pulsating cavities.	12
Table II. Data for ventilated cavities.	14

SYMBOLS

a_g	speed of sound of the gas contained in the cavity
k	reduced frequency of pulsation = $\omega l/U$
l	cavity length
l_o	cavity length/chord length
M^*	equivalent Mach number = $\left(\frac{\rho U_c^2}{\rho_g a_g^2} \right)^{1/2}$
P_c	cavity pressure
P_∞	ambient pressure
R	gas constant
T	temperature of the water
U_c	velocity along cavity
U_∞	uniform free stream velocity
α	chord length/breadth of channel
β	chord length/cavity length
γ	half-angle of wedge
ρ	density of the free stream
ρ_g	density of gas contained in the cavity
σ	cavitation number
ω	frequency of pulsation



I. INTRODUCTION

Cavity pulsations were first observed in 1961 by Silberman and Song (1)*. A two-dimensional, vertical, free jet water tunnel was used in their experiment. Definite pulsations of the cavity were observed at a critical cavitation number. One of the conclusions drawn by Silberman and Song was that a free surface was necessary for these pulsations to take place.

Then in 1962, Song (2) did some analytical work on pulsating cavities and compared his results with experiments. In general, good agreement was obtained. Again, Song concluded that a free surface was essential for pulsations of cavities.

Stimulated by these works, Hsu and Chen (3) conducted a theoretical analysis of pulsating cavities in an infinite medium. They hypothesized that cavity resonance was an interaction between the flow around the cavity and the compression and expansion of the gas inside the cavity. Therefore, there was no need for a free surface in order to have cavity pulsations.

* Numbers in parentheses refer to References listed at the end of the paper.

APPENDIX

The following table shows the results of the experiments conducted on the effect of the concentration of the solution on the rate of reaction. The concentration of the solution was varied from 0.1 M to 0.5 M, and the rate of reaction was measured by the time taken for the reaction to complete. The results show that the rate of reaction increases with increasing concentration of the solution.

Concentration of Solution (M)	Time taken for reaction to complete (s)
0.1	120
0.2	60
0.3	40
0.4	30
0.5	20

The results of the experiments show that the rate of reaction increases with increasing concentration of the solution. This is because a higher concentration of the solution means there are more particles of the reactants in a given volume, which increases the chance of collisions between the particles and thus the rate of reaction.

Further experiments were carried out in 1964 by Schiebe and Wetzel (4) in a vertical free jet water tunnel and in a towing tank. It was from a comment in this latter paper that the topic for this thesis arose. It was stated that no experimental work had been performed to verify the theory of Hsu and Chen. The author's survey of the literature in the field revealed that there has been very little experimental work conducted in ventilated cavities.

The purpose of this thesis is twofold.

1. The determination of the feasibility of conducting ventilated cavity experiments in the MIT Propeller Tunnel.
2. An attempt to verify the theory set forth by Hsu and Chen (3).

* Numbers in parentheses refer to References listed at the end of the paper.

II. PROCEDURE

Description of Equipment

The experiments were conducted in the recently remodeled MIT Propeller Tunnel. The test section is 20 inches by 20 inches by 54 inches and has 2-inch plexiglass windows on all four sides in order to facilitate visual observations.

The tunnel was designed to operate from atmospheric pressure down into the vacuum range. Pneumatic control equipment is used to maintain the tunnel pressure at the desired level. This pressure is the value used as the pressure at infinity in the calculations. Pressure in the cavity is measured by a mercury manometer. The pressure tap is located approximately 4 inches behind the wedge and is flush with the inside face of the plexiglass window. However, during the last series of experiments, this pressure tap was modified so that it extended into the cavity $1/2$ inch.

The velocity in the test section is determined by the speed of the impeller which moves the water through the tunnel. The maximum velocity obtainable in the test section is approximately 33 feet per second.

THEORY

The first part of the theory is the definition of the system. The system is defined as a set of elements that interact with each other in a specific way. The elements are represented by nodes in a graph, and the interactions are represented by edges.

The second part of the theory is the description of the system's behavior. The behavior is described by a set of rules that govern the interactions between the elements. These rules are often expressed in the form of a state transition diagram or a set of equations.

The third part of the theory is the analysis of the system's properties. The properties are analyzed by studying the system's behavior under different conditions. This analysis often involves the use of mathematical tools such as graph theory, probability theory, and statistics.

The fourth part of the theory is the application of the theory to a specific problem. The application involves the use of the theory to model a real-world system and to predict its behavior. This application often involves the use of computer simulations and data analysis.

The fifth part of the theory is the validation of the theory. The validation involves the comparison of the theory's predictions with experimental data. This validation often involves the use of statistical tests and the analysis of the results of the experiments.

The sixth part of the theory is the discussion of the theory's limitations. The limitations are discussed by identifying the assumptions that underlie the theory and by analyzing the consequences of these assumptions. This discussion often involves the use of mathematical tools such as asymptotic analysis and perturbation theory.

The seventh part of the theory is the conclusion. The conclusion summarizes the main results of the theory and discusses the implications of these results. This conclusion often involves the use of mathematical tools such as theorems and lemmas.

The eighth part of the theory is the bibliography. The bibliography lists the references used in the theory. This bibliography often involves the use of mathematical tools such as citation analysis and the analysis of the results of the experiments.

Figure I

Front view of test section.

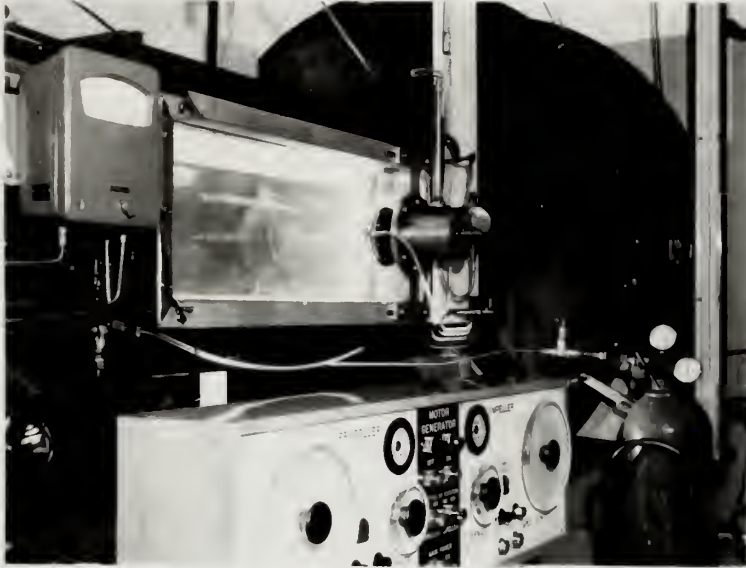


Figure II

Rear view of test section.

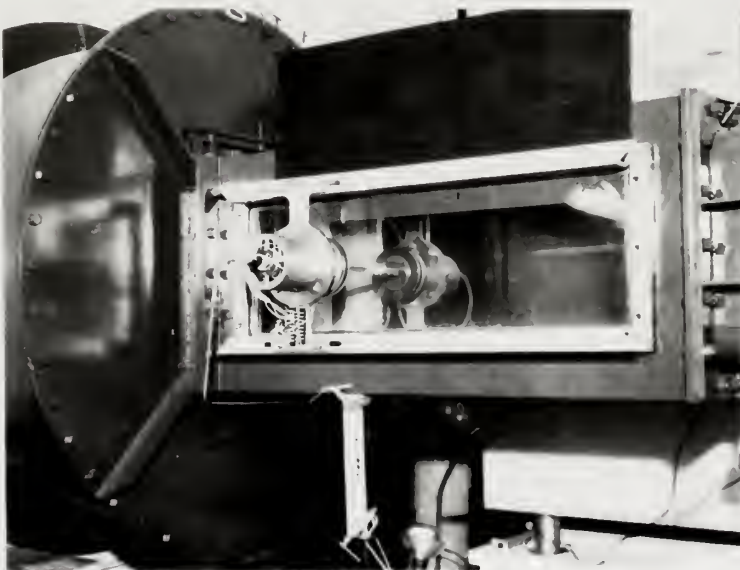


Figure 1 shows the control panel, the pneumatic pressure controller, several manometers, and the air cylinder used to ventilate the cavity. Further description of the tunnel is contained in Reference (5).

The hydrofoil used is a wedge shape with a vertex angle of 8.2 degrees and a chord length of 3.5 inches. In the base of the hydrofoil is a 1/4 inch O.D. copper tube which leads to the exterior of the tunnel through the mounting brackets (see Figure 2). The air supply can be connected at this point or the cavity can be vented to the atmosphere. In the copper tube in the base of the foil are 13 No. 80 holes. The mounting brackets for the wedge are described in detail in Reference (6).

Method

First, a vacuum was drawn on the propeller tunnel. The pressure reached was approximately 100 mm of Hg. absolute. The water velocity in the test section was then increased to a speed above 20 feet per second in order to form a natural cavity behind the wedge. At this point the cavity pressure and the water velocity

were recorded. A high vacuum had to be used because at pressures near atmospheric pressure the hydrofoil was observed to vibrate and bend in the middle. At the higher vacuums there are many more air bubbles present in the tunnel which have a damping affect on the vibration of the foil. Also at the low pressures there exists on the outside of the mounting brackets a force of 14.7 psi whereas on the inside the force is only about 4 psi. This puts additional restraint on the foil. These facts have a tendency to reduce the phenomenon observed at pressures near atmospheric pressure.

Once a natural cavity was established, the valve in the line to the air supply (1500 psi) would be opened slowly. The air entering the cavity was regulated to about 400-500 psi. As the length of the cavity increased, the cavity pressure and corresponding length were recorded. A length of approximately 30 inches was the maximum obtainable in the test section. A length greater than this would have taken the cavity into the diffuser section of the tunnel.

A pitot tube was used to measure the velocity in the test section. This was done without the wedge in the tunnel. Also the tunnel was under a vacuum of 200 mm

of mercury. The pitot tube readings were converted to velocities corresponding to the rpm used to control the flow velocity. This curve is shown in Figure III. There existed a difference in these velocities when compared to the velocities determined at atmospheric pressure.

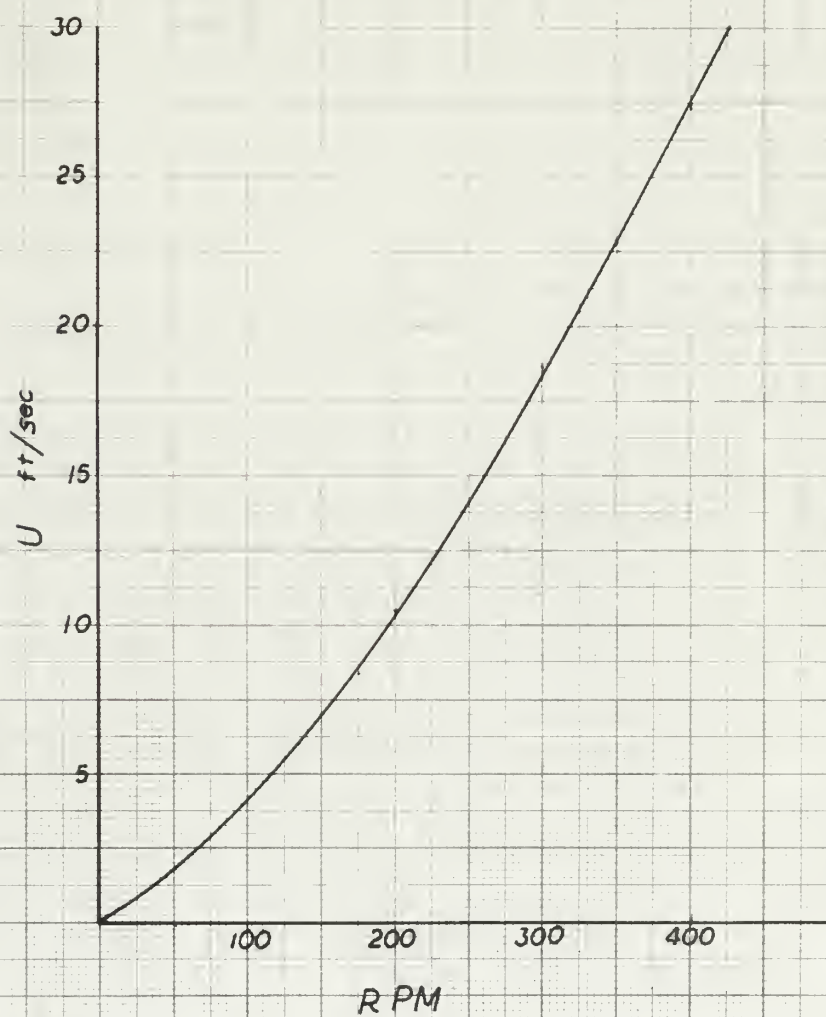
During one set of runs of the experiment, polaroid photographs were taken some of which will be discussed later. It was difficult to observe anything in some of the pictures due to the high air content of the water with ventilated cavities. An attempt was made to take high-speed movies. A Fastex 16-mm camera was used with a frame speed of 1000 frames per second. Since the area that the author was interested in photographing was approximately 30 inches wide, the camera had to be located away from the tunnel about six feet. Good pictures could not be taken at this distance. The camera could not be moved closer since a wide angle lens was not available.

The Propeller Tunnel may be operated with a free surface by dumping some of the water into a storage tank. This was done during the first phase of the experiment.

Figure III

RPM versus Flow Velocity
(Tunnel pressure = 200
mm of mercury.)

5/7/68 RJK



The water level was lowered to about 3 inches below the top of the test section; the speed was varied; and air was introduced into the base of the wedge.

III. RESULTS

Pulsating Cavities

The results concerning the pulsation of ventilated cavities are inconclusive. No pulsations were observed in any of the cavities generated. Figure IV shows the cavity resonance conditions for a 15 degree wedge. This figure is adapted from Reference (3). The curves are a plot of cavity pressure over the pressure at infinity versus the flow velocity of the fluid and they represent the first three stages * of pulsation of the cavity at five feet below a free surface. Hsu and Chen (3) assume that the presence of this free surface does not affect the results of their theory, i.e., pulsations in an infinite medium. Cavity resonance is possible when p_c / p_∞ and U_c lie along one of these curves.

Plotted on Figure IV are data interpreted from Silberman and Song (1). One set of points is for a half-span normal plate (1/8 inch plate, 10 inch jet), and the other set is for a half-span hydrofoil (Modified Tulin-Burkhart, 2 1/2 inch chord) at a 12 degree angle of attack in a 10 inch jet. The points for the second and third stages are in agreement with the

* The stages refer to the number of waves appearing on the cavity.

Cavity Resonance Conditions

from Reference (3)

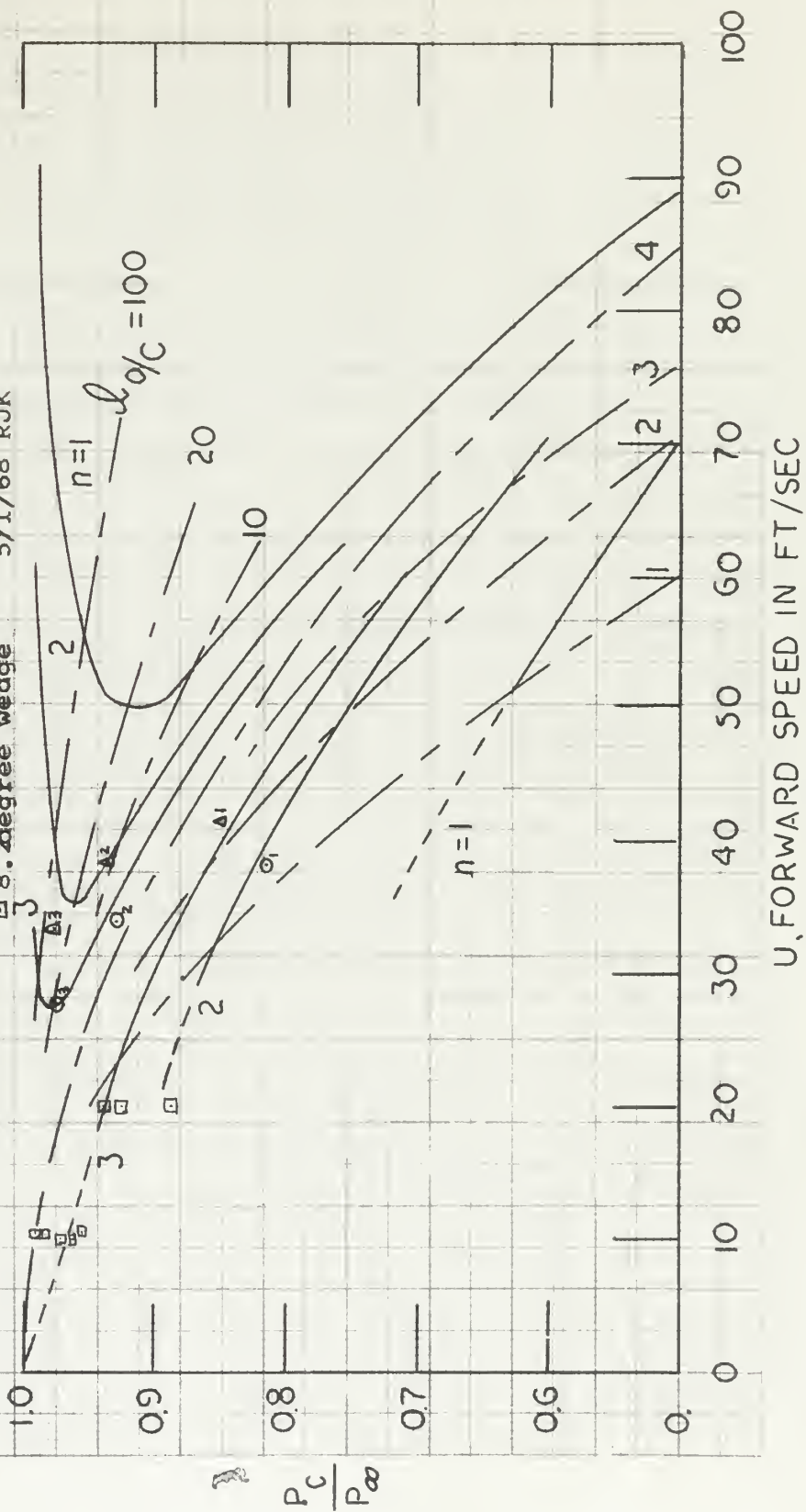
Ref. (1)

1/8 in. - plate

Δ Hydrofoil @ 12 degree

angle of attack

8. 2 degree wedge

$$n=1 \quad \frac{1}{n} = 100$$


curves of Hsu and Chen. The data for the first stage do not agree at all.

Points for a 4.1 degree wedge with a 3.5 inch chord are also plotted. Although some of these points lie on or near the resonant conditions, no pulsations were observed by the author.

To determine if pulsations are possible, the conditions for pulsations are taken from Hsu and Chen (3). These are

$$F_2(k_n/2) = 0 \quad (1)$$

$$M^*{}^2 = \frac{1}{\sigma_0 \ln(l_0/4)} - \frac{16}{k^2} F_1(k_n/2) \quad l_0 \neq 4$$

where F_1 and F_2 are equations of Bessel functions with arguments $k/2$, and these are given in Reference (3).

The following table gives the theoretical values of $k/2$ and $\frac{16}{k^2} F_1(k/2)$ for four stages when $F(k_n/2) = 0$.

Table I
Theoretical results

n		1	2	3	4
k/2	$l_0 > 4$	4.2	7.4	10.75	13.7
	$l_0 < 4$	2.75	5.9	9.0	12.1
$\frac{16}{k^2} F_1$	$l_0 > 4$	0.192	0.097	0.055	0.044
	$l_0 < 4$	-1.11	-0.32	-0.16	-0.095

Figure IVa

Equivalent mach number versus
steady part of cavitation number.

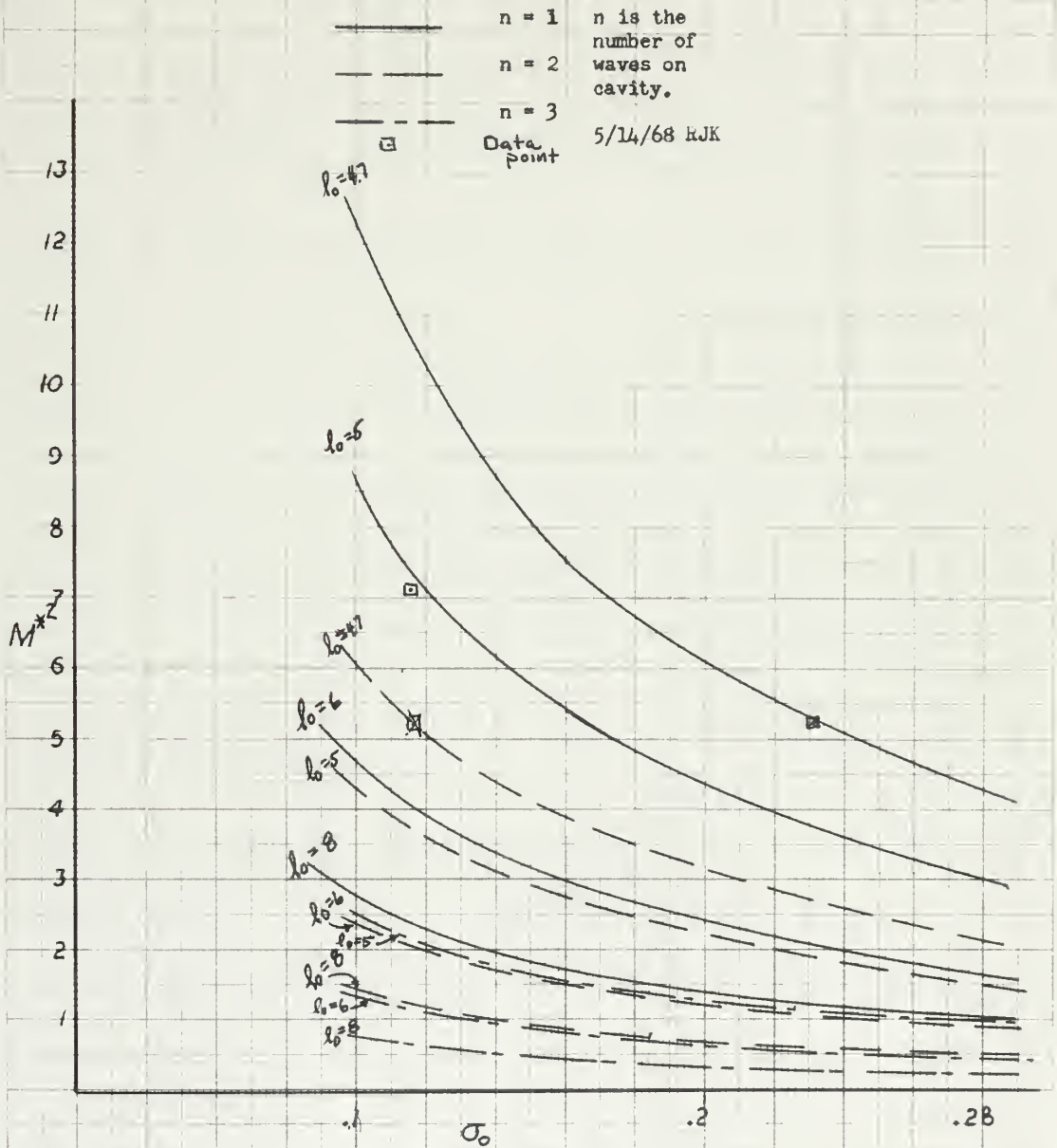


Table II

Data for ventilated cavities.

P_{∞} mm of Hg	P_c mm of Hg	U_c fps	l in	l_0
79	53	23.3	18.5	5.15 *
109	89	16.9	9	2.57
84	46	21.4	21.5	6.15
108	81	19.4	14	4
79	37	23.8	22	6.3
81	37	21.7	19	5.4
83	30	22.7	22	6.3
92	59	21.0	16.5	4.7 *
104	73	19.8	6	1.7

* indicates data that was in the pulsating region.

Figure IVa is a plot of equation (1) with various values given for ℓ_0 and n . Since the minimum cavitation number is 0.104, Figure IVa starts near 0.1. This minimum cavitation number is discussed later.

With the data taken during the experiments, the equivalent Mach number is calculated.

$$M^*^2 = \frac{p}{\rho g} \frac{U_c^2}{A g^2} \quad (2)$$

$$P_c = \rho g R T \quad (3)$$

$$A g^2 = R T \quad (4)$$

therefore,

$$M^*^2 = \frac{p}{P_c} \frac{U_c^2}{A g^2} = \frac{0.696}{P_c} \frac{U_c^2}{A g^2} \quad (5)$$

with P_c given in mm of mercury and U_c given in feet per second. The cavitation number is also calculated from the given data. From the calculations made on the data, two points were found to lie on the given curves (see Figure IVa). However, no pulsations were observed under these conditions.

While running the tunnel with a free surface, an attempt was made to reproduce some of the results obtained by Silberman and Song (1) and Schiebe and Wetzel (4). Again in the ventilated cavities no pulsations were observed. Other experimenters have had difficulty in reproducing the results of Silberman and Song (10).

Ventilated and Natural Cavities

While no definite results were collected concerning the pulsation of ventilated cavities, some data were gathered on the natural and ventilated cavities that were produced. These data are plotted in Figure V along with some theoretical curves. The generally accepted correlation parameter is the cavitation number, σ , where

$$\sigma = \frac{P_o - P_c}{\frac{1}{2} \rho U_\infty^2} \quad (6)$$

Figure V is a plot of sigma versus beta (B).

Since the experiment was conducted with solid walls, a correction factor was applied to the velocity to determine the cavitation number. This correction was also used since the velocity measurements taken for the test section were done so without a hydrofoil mounted. Following the manner of Birkhoff (7), the simplified form of Bernoulli's equation

$$\frac{1}{2} \rho U_\infty^2 + p_\infty = \frac{1}{2} \rho U_c^2 + p_c \quad (7)$$

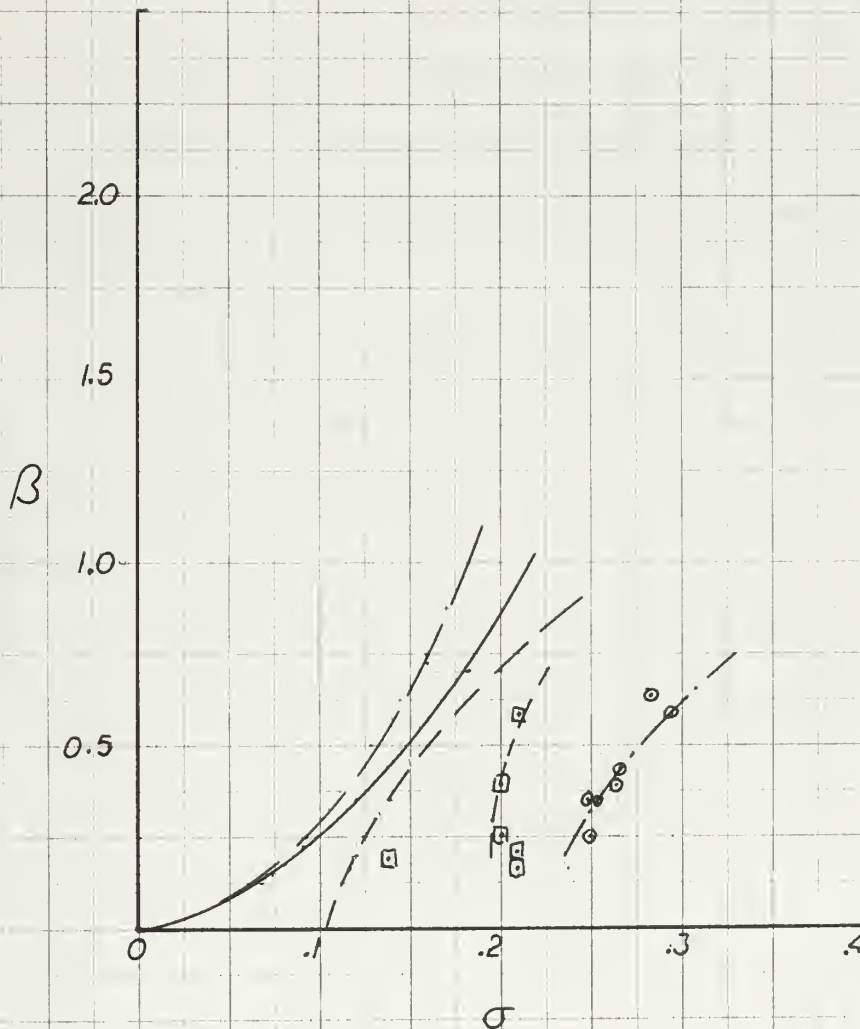
is used. When this equation is solved for $p_\infty - p_c$ and is substituted into equation (6), the result is

$$\frac{U_c}{U_\infty} = \sqrt{\sigma + 1} \quad (8)$$

Figure V

Cavitation Number versus Chord Length
to Cavity Length Ratio

--- Eq. $\alpha = 0$ } $\gamma = 4.1^\circ$
 --- Eq. $\alpha = .175$ }
 \circ Natural Cavities } $\gamma = 4.1^\circ$
 \square Ventilated Cavities } $c = 3.5 \text{ in}$
 5/7/68 RJK



Upon linearizing this equation we obtain

$$U_c = U_\infty \left[1 + \frac{1}{2} \sigma \right] \quad (9)$$

The value of sigma used in equation (9) is the one calculated from the theoretical results of Cohen and Gilbert. This is discussed below. The calculated U_c is then used to determine the experimental cavitation number. The results are approximately the same as those that would have been derived if the reduction in cross sectional area of the flow due to cavity width had been used to determine U_c .

One of the curves (Figure V) is the asymptotic results for an inclined wedge as developed by Leehey (8). This result is valid for $\sigma \ll 1$ ($l_0 \gg 1$) and is as follows:

$$\sigma = \frac{8}{\pi} \gamma l_0^{-\frac{1}{2}} \quad (10)$$

This theory is for an infinite medium.

The other two theoretical curves plotted were determined from the results of Cohen and Gilbert (9) dealing with wall effects on cavity flow. The reduced equation for an infinite stream is plotted. The equation for this curve is

$$\frac{\sigma}{1 + \frac{\sigma}{2}} = \frac{4\gamma}{\pi} \left\{ \sqrt{\beta(1+\beta)} + \ln \left[\sqrt{\beta} + \sqrt{1+\beta} \right] \right\} \quad (11)$$

At high cavity lengths (low B) equations (10) and (11) agree quite well. But the curves begin to separate as the length decreases.

The equation that takes into account the solid walls is

$$\begin{aligned} \frac{\sigma}{1 + \frac{\sigma}{2}} = \frac{2\gamma}{\pi} & \left\{ \coth \frac{\pi a}{2\beta} \tanh^{-1} \left[\frac{\sqrt{\sinh \pi a \sinh \frac{\pi a(1+\beta)}{\beta}}}{\cosh \frac{\pi a(1+2\beta)}{2\beta}} \right] \right. \\ & \left. + \tanh^{-1} \left[\frac{\sqrt{\sinh \pi a \sinh \frac{\pi a(1+\beta)}{\beta}}}{\sinh \frac{\pi a(1+2\beta)}{2\beta}} \right] \right\} \end{aligned} \quad (12)$$

This equation is plotted with a half-wedge angle of 4.1 degrees, a channel breadth of 20 inches, and a chord length of 3.5 inches.

The limiting cavitation number under the test conditions is calculated from Cohen (9):

$$\frac{\sigma_{\infty}}{1 + \frac{\sigma_{\infty}}{2}} = \frac{4\gamma}{\pi} \cosh^{-1} \left[e^{\pi a} \right] \quad (13)$$

where σ_{∞} = cavitation number at $B = 0$. The value of this limit is 0.104.

The experimental results are plotted for natural cavities and for ventilated cavities. The general shape of the curves agrees quite well with the theoretical curve with the presence of walls taken into account. However, there is a discrepancy of about .12 in the range of cavitation numbers covered.

Study of Ventilated Cavities

It is possible to conduct experiments on ventilated cavities in the MIT Propeller Tunnel, but there are some limitations. One is the maximum velocity obtainable without doing possible damage to the tunnel. The author was able to reach only a velocity of approximately 25 feet per second. Even at this speed the tunnel near the test section began to vibrate causing the pneumatic equipment mounted on the tunnel to vibrate. Also at this speed there existed considerable noise in the diffuser section and in the turning vanes when air was introduced into the cavity.

The other limitation is the extent to which visual observations are possible. As mentioned earlier, polaroid pictures were taken, but they were of such a nature that one had to know what to look for in order to see the re-entrant jet and the trailing edge of the cavity.

The pictures taken of the natural cavities clearly show the top side of the test section (all pictures of re-entrant jets were taken from the bottom) so that photographing through the 2 inches of plexiglass and the water is not a problem.

Figure VI shows a drawing of the general shape of a natural cavity. When the cavity is first formed, the re-entrant jet impinges on the base of the wedge (over the entire span). The jet has nearly a rectangular shape when viewed from the top or bottom. As the speed is increased or as the pressure is decreased, the cavity length increases. The re-entrant jet retains its approximately rectangular shape as the cavity grows and it impinges on the center portion of the wedge. Eventually the jet no longer strikes the wedge but is as shown in Figure VI.

The problem of observing ventilated cavities is much more difficult than with natural cavities. At about 19 feet per second the re-entrant jet was verily well defined. Figure VII shows a drawing of the general nature of a ventilated cavity. It differs from the natural cavity in that it does not have the rectangular shape across the trailing edge of the cavity. This is due to the flow

Figure VI

Drawing of the general nature of the
re-entrant jet of a natural cavity.
(Not to scale.)

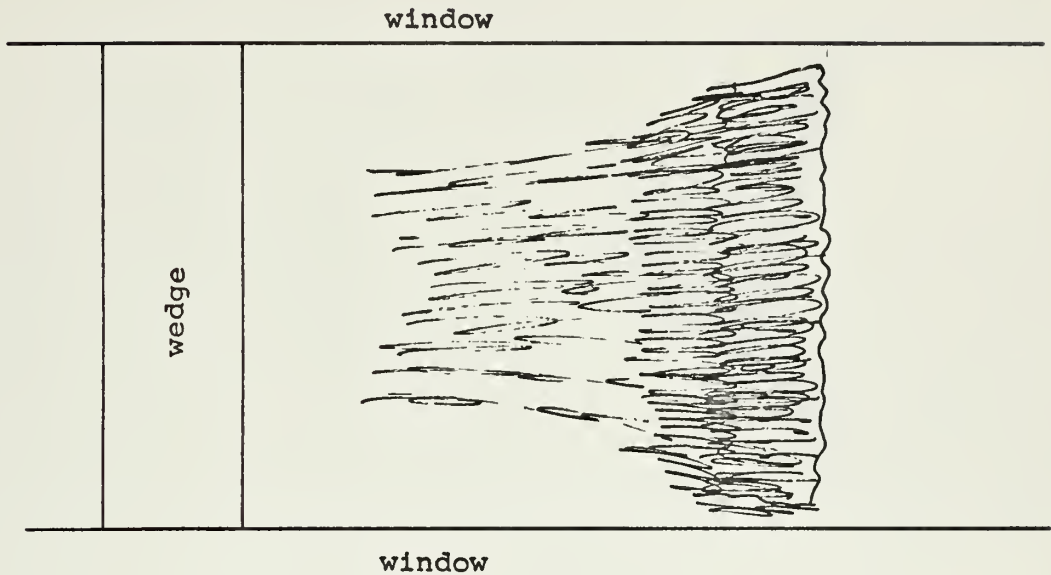
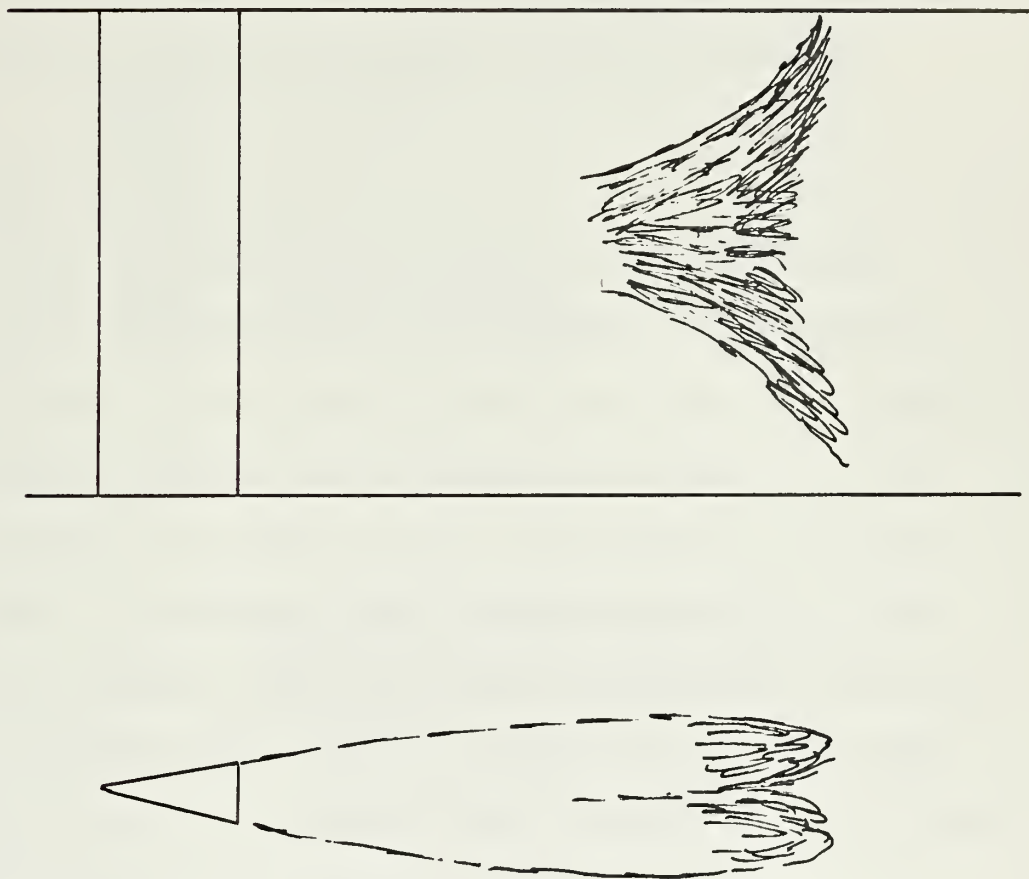


Figure VII

Drawing of the general nature of the
re-entrant jet of a ventilated cavity.
(Not to scale.)



of air in the cavity that is being introduced through the base of the wedge. As the air injection increased the cavity grew until it reached a point where the center part of the re-entrant jet was completely disrupted. In this case the inflow of air was much greater than the outflow through entrainment in the re-entrant jet.

During one experimental run, the air inlet to the base of the wedge was left open to the atmosphere. The velocity of the water was about 11 feet per second. Under these conditions the parameter that was varied was p_∞ . As the tunnel pressure was reduced the cavity length increased and p_c remained less than p_∞ . The length of the cavity at this point was about 14 inches. Then as the pressure was decreased beyond 427, p_c was less than p_∞ but there existed no substantial increase in cavity length beyond 14 inches. At the point where $p_c > p_\infty$, the cavitation number is negative and the theory for cavity flows does not apply.

The water tunnel may be operated with a free surface, but at high speeds the water level builds up in the upstream direction causing the flow through the test section to be at an angle from upstream to downstream. Through

Figure VIII

Ventilated cavity with free surface.



Figure IX

Bottom view of Figure VIII.



trial and error the wedge position was adjusted so that the effective angle of attack with respect to the flow was zero. Figures VIII and IX show a side view and a bottom view of the wedge with air being introduced. With a vacuum being drawn on the tunnel, it is observed that the air rises immediately to the free surface in the downstream direction. Only short cavities were produced in this manner. Large bubbles are observed in these two pictures even though the size of the holes in the base of the wedge are only No. 80. This is due to the pressure in the tunnel being lower than the air entering causing the bubbles to expand.

IV. DISCUSSION OF RESULTS

The data of Silberman and Song (1) plotted in Figure IV agrees very well with the theory of Hsu and Chen even though the shapes of the bodies used are different and in their experiments a free surface was present. This difference in shapes may attribute to the lack of agreement for the first stage.

The data plotted by the author in Figure IV lay in the low speed range (10-20 fps) of the curves. The fact that high speeds were not obtainable in the present test section contributed to the lack of cavity pulsations. A prospect for future experimentation is the use of a collapsable nozzle to give a greater area reduction that may be inserted into the present test section. Thus higher velocities will be obtainable.

The data points plotted in Figure V tend to verify equation (12) which takes into account the effect of solid boundaries. Also as expected the ventilated cavities are longer than the corresponding natural cavities. There does appear to be, however, a discrepancy in the cavitation numbers for the theory and the experiment. The author attributes this mainly to method in which pressures were measured. The measured pressures inside

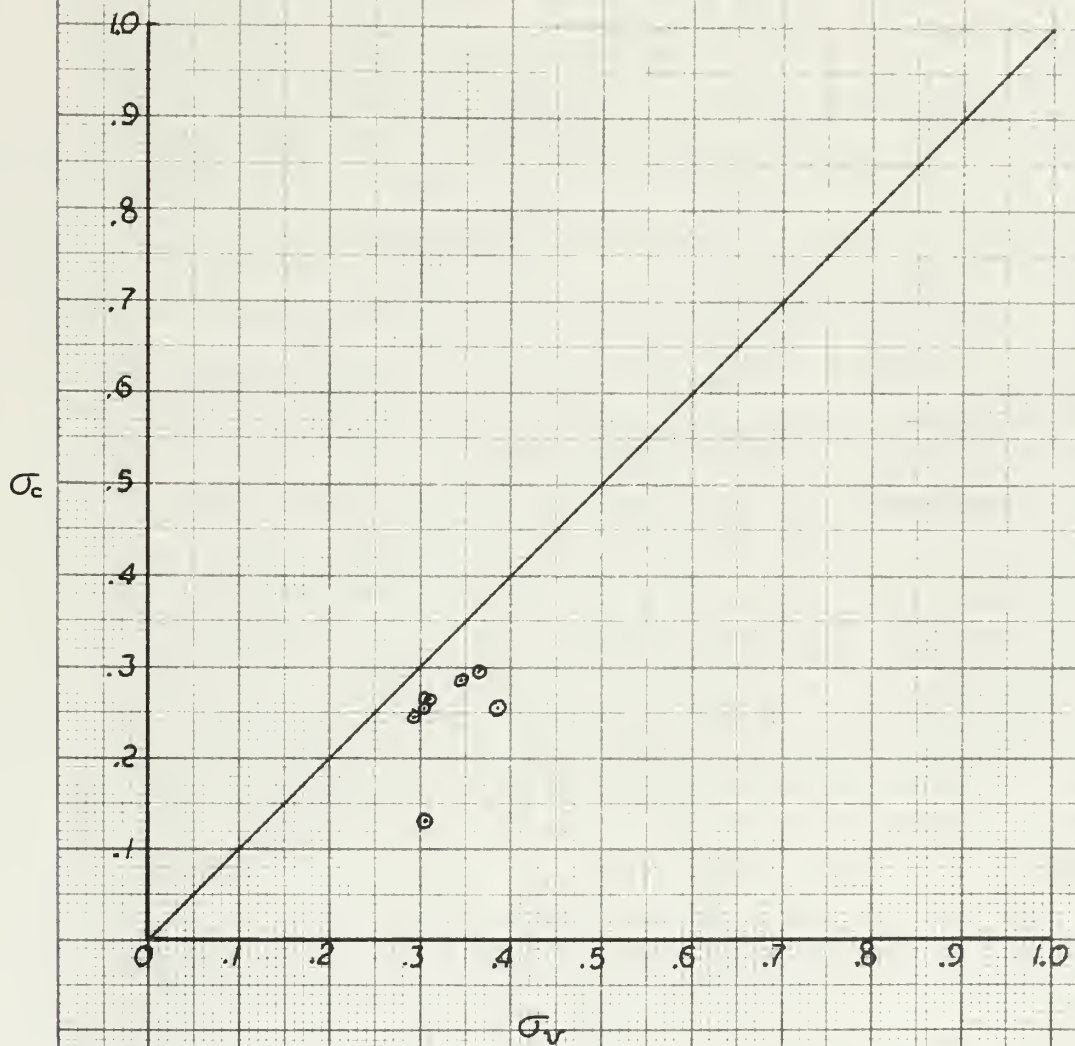
the natural cavities were generally larger than the vapor pressure of water. The discrepancy is shown in Figure ~~VIII~~X.

Initially cavity pressures were measured with the pressure tap flush with the test section wall in the cavity region. The device used was a crude mercury manometer made by the author. The data taken using this pressure tap were widely dispersed. The tap was modified so that it extended into the cavity about 1/2 inch. The data taken then were more uniform.

The pressure used as p_{∞} was the static pressure measured at the forward end of the test section. This was the pressure used to control the pneumatic equipment which regulated the vacuum in the tunnel. At high speeds this pressure was observed to vary greatly. The probable cause of this is the boundary layer effect at the entrance to the test section. Another source of error was in the difficulty in maintaining the lines leading to the manometers filled with water when a low vacuum was being drawn on the tunnel.

Figure X

Comparison between cavitation number based on vapor pressure and cavitation number based on measured cavity pressure.



V. CONCLUSIONS AND RECOMMENDATIONS

1. It was not possible to produce pulsating cavities in the MIT Propeller Tunnel. Therefore, no conclusions may be drawn in regards to the theory developed by Hsu and Chen (3).
2. The theory concerning wall effects appears to be quite good. The shape of the experimental results verifies this although there is a discrepancy in the cavitation numbers. This is due to the unsophisticated method of measuring the pressures.
3. The study of cavity flows can be accomplished in the MIT Propeller Tunnel; however, visual observations are limited when ventilation is used since the water fills up with air bubbles, and these are circulated through the tunnel.
4. Further investigations of pulsating cavities might be conducted in the tunnel. There is the possibility of using different shapes and wedges with larger half-angles.
5. A nozzle that can fit into the existing test section may be designed to give a smaller exit area. Higher speeds would then be possible.
6. Re-entrant jets may be studied to compare with theory.

VI. REFERENCES

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